Ecological Engineering 57 (2013) 413–421

Contents lists available at SciVerse ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Nutrient processing in a novel on-site wastewater treatment system designed for permeable carbonate sand environments

Douglas R. Tait[a,*], Dirk V. Erler[a], Andrew Dakers[b], Leigh Davison[a], Bradley D. Eyre[a]

[a] Centre for Coastal Biogeochemistry, School of Environment, Science and Engineering, Southern Cross University, Lismore, Australia
[b] ecoEng Ltd, Christchurch, New Zealand

ARTICLE INFO

Article history:
Received 2 November 2012
Received in revised form 18 March 2013
Accepted 6 April 2013
Available online 2 July 2013

Keywords:
EcoTrench
On-site treatment
Effluent
Nutrient
Groundwater
Permeable carbonate sands

ABSTRACT

This study was the first to develop, install and examine a secondary treatment system for domestic wastewater specific to permeable carbonate sand systems. The 'ecoTrench' (eT), relied on effluent passing through a number of different treatment layers including a coconut husk humus ecology, a saturated trench and unsaturated carbonate sands. An eT was installed on a residential property on the main island of Rarotonga in the Cook Islands and received primary treated effluent from a septic tank over a 21 month period from May 2009 until February 2011. Nutrient removal efficiencies for the eT averaged 63% of total phosphorous and 43% of total nitrogen. The eT was an effective nitrifyer of NH_4^+ to NO_3^- with almost complete attenuation of NH_4^+ as effluent passed through the system. Uptake rates of NH_4^+ averaged 36.7 ± 4.1 mmol m^{-3} h^{-1} as wastewaters left the saturated trench. The addition of labelled stable isotope ($^{15}NH_4^+$), showed that simultaneous nitrification/denitrification was occurring in both aerobic and anaerobic treatment layers. Elevated concentrations of dissolved organic nitrogen (DON) were seen as effluent left the saturated treatment layer before largely being attenuated as effluent moved down through the sediment profile. This may have contributed to a significant build-up of NO_3^- as effluent moved towards groundwater largely due to inhibited denitrification and the mobilization and remineralisation of previously assimilated DON. The eT represents an efficient and effective way to reduce nutrient loading to groundwater and can work well within the constraints of many island communities based in permeable carbonate sand systems.

1. Introduction

Anthropogenic nutrients entering groundwater have been linked to the nutrient enrichment of receiving waters (Vitousek et al., 1997). This excess nutrient has led to a range of impacts including: adverse human health conditions (Townsend et al., 2003); eutrophication (Rabalais, 2002); and impacts on global nutrient cycling (Galloway et al., 2004). Agriculture has long been assumed to be the leading cause of nutrient inputs into groundwater, however human and animal wastes are now recognised as a leading pollutant of shallow aquifers (Wakida and Lerner, 2005). Shallow aquifers in the porous carbonate sand islands of the South Pacific are particularly susceptible to the impacts of increased nutrient flows from human and animal derived wastewater. Commercial and residential development on South Pacific islands tends to be concentrated on the coastal dune systems that fringe marine waters and waste management is largely decentralised. The large grain size and porosity of sediments in these carbonate sand systems mean that nutrient rich waters reach groundwater quickly with little opportunity for nutrient reduction through filtration or microbial treatment. Importantly, ineffective on-site treatment systems used in many of the islands may contribute to excess nutrient loads reaching receiving waters.

Decentralised, or on-site, effluent treatment systems are used throughout the world to reduce nutrient and pathogen loads entering ground and surface waters. In many South Pacific countries, the traditional on-site system consists mainly of a one or two chamber septic tank attached to a soak pit. The quiescent and anaerobic conditions in septic tanks allow for the settlement and breakdown of effluent organic and suspended solids, however they have been shown to be largely ineffective at reducing both the nitrogen and phosphorous concentrations of effluent (Gill et al., 2009). The soak pits attached to the septic tank consist of a mostly unlined hole filled with large rocks or gravel. While providing an effective means of reducing any surface flow of wastewaters, these soak pits provide an almost direct pathway for nutrient laden wastewater to

* Corresponding author at: Centre for Coastal Biogeochemistry, Southern Cross University, Lismore, NSW, Australia 2480. Tel.: +61 2 6688 6429; fax: +61 2 6621 2669.
E-mail address: douglas.tait@scu.edu.au (D.R. Tait).

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http://dx.doi.org/10.1016/j.ecoleng.2013.04.027

groundwater. A range of alternative on-site systems such as composting toilets (Davison et al., 2006), biofilm reactors (Clifford et al., 2010), denitrification beds (Warneke et al., 2011), subsurface (Vymazal, 2009) and vertical (Brix and Arias, 2005; Kantawanichkul et al., 2009) flow constructed wetlands are available, but to date, no attempt has been made to design and test an on-site system specific to the needs and constraints of South Pacific carbonate sand systems.

Unlike the quartz substrates typically used as filtration media, the carbonate grains of tropical islands have not been studied extensively in the context of wastewater treatment. The structure of these sediments may significantly influence nutrient dynamics through the soil profile because carbonate grains have high porosity and permeability, high bacteria abundance and a large pH buffering capacity (Rasheed et al., 2003). The viral and bacterial activity in coarse carbonate sands can exceed the activities in the water column by three orders of magnitude as bacteria may thrive in microenvironments within porous grains (Wild et al., 2006). These microenvironments may prove conducive to facilitating nitrogen cycling processes such as nitrification, denitrification, anammox and dissimilatory nitrate reduction to ammonium (DNRA) as well as phosphorous cycling processes such as adsorption/desorption, assimilation and plant and microbial uptake (Santos et al., 2012; Eyre et al., 2013). Designing wastewater treatment systems with treatment zones which are particularly conducive to these processes taking place is crucial for facilitating greater nutrient removal.

The use of stable isotopes has proved useful in differentiating nutrient cycling processes. The addition of labelled nitrogen has been used successfully to describe nitrification/denitrification reactions in constructed wetlands (Kadlec et al., 2005; Reinhardt et al., 2006; Erler et al., 2010) and wastewater affected groundwater (Aravena and Robertson, 2005). In on-site systems, O'Luanaigh et al. (2010) recently used labelled nitrogen to describe nitrogen kinetics in horizontal subsurface flow reed beds. However, the much more widespread application of stable isotopes to evaluating on-site systems would greatly increase the understanding of nutrient removal potentials.

This study, for the first time, developed and evaluated a secondary effluent treatment system specific to permeable carbonate sand systems. We propose that by passing effluent through an "ecoTrench" (eT), nutrient concentrations will be significantly reduced. The eT relied on effluent passing through a number of different treatment layers including a coconut husk humus ecology, unsaturated carbonate sands, a saturated trench and coarse unsaturated carbonate sands. Monitoring of nutrient concentrations was conducted over a 21 month period to test the long term viability of system. In order to differentiate and quantify nutrient cycling processes within the different layers both conservative and stable isotope tracers were used.

2. Methods

2.1. Study site

The study was undertaken on Rarotonga, in the Cook Islands in the central South Pacific (21°14′S 159°47′W). Rarotonga is a lagoon fringed, volcanic and karstic island. The interior of the island is characterised by peaks of up to 450 m and soils that consist of volcanic basaltic and phonolitic sediments. At the base of the peaks, alluvial fans and terraces have formed through the weathering of the upland volcanic rocks. The coastal plains below the alluvial fans consists of poorly drained inland depressions or taro swamps and a raised ridge of coral sand and gravel which is bordered by lagoon waters (Leslie, 1980). The lagoon is characterised by a reef flat which ranges between 500 m to 1500 m from shore.

An eT was installed on a private domestic property on the coastal plain dominated by free draining carbonate sediments. The chemical composition of the carbonate sediments was <1% calcite, <1% quartz, ∼26% Mg-calcite, and ∼72% aragonite. A thick limestone rock layer at a depth of ∼4 m marked the uppermost boundary of the water table with sediments above this layer remaining largely unsaturated. The site was bordered on the landward side by a taro swamp (∼40 m from the eT) and the main ring road of Rarotonga on the seaward side (∼150 m from the lagoon).

The trench was installed in March 2009 and first received domestic effluent loading from a septic tank on 13 April 2009. Sampling was conducted on 19–21 May 2009 and on 17–21 October 2009. In February 2010 the septic tank was replaced with a secondary treatment system (BioPod, Biolytix). The secondary treatment system was designed to separate the solids from the liquid wastewater and aerate the treated water. A third sampling period was conducted on 22–24 March 2011. In total the eT was monitored for 21 months.

2.2. Ecotrench design and sampling

The average metered effluent inflows to the eT were ∼1440 L d^{-1} of effluent from a sump linked to the septic tank or secondary treatment unit (Fig. 1). The effluent was delivered in 200 L doses via a submersible pump at 50 L min^{-1}.

Effluent entered the eT through a 40 mm perforated PVC pipe above the treatment layers. A concrete block cavity surrounding the inlet pipe directed effluent though the different treatment zones as follows. Effluent percolated down from the inlet pipe through a humus arch consisting of fibrous coconut husk. This husk layer was designed to trap particulate material and increased the surface area available for biomat build-up. Effluent then passed through an unsaturated 200 mm layer of coarse carbonate sand. A layer of geofabric underneath the sand layer stopped fine sediment particles moving farther through the system. Beneath the geofabric layer effluent entered the denitrifying trench which consisted of a saturated zone filled with ∼20 mm coarse gravels. A thick (250 micron) polyethylene sheet lined the bottom of the eT to stop effluent from prematurely intruding into groundwater. The difference in hydraulic head between the height of the concrete block walls and the sides of the eT caused effluent to flow out of the saturated zone towards the edge of the eT as further effluent was introduced through the inlet pipe. Surface sediments were planted with local fruiting trees and grasses to aid in evapotranspiration and nutrient uptake as effluent moved horizontally out of the trench. Once reaching the edge of the polyethylene layer, the effluent percolated down to groundwater through the coarse carbonate sand substrate.

2.3. Sampling

Effluent was sampled from the eT inlet, two full stop lysimeters (FullStop Wetting Front Detector) placed under the humus arch and initial sand layer, eight piezometers placed at shallow and deep sampling points within the lined saturated trench (Trench Sh and Trench Dp respectively) and eight suction lysimeters placed at 500 mm (Sand Sh) and 800 mm (Sand Dp) below the surface in the unsaturated carbonate sand region at the edges of the eT (Fig. 1). During the second sampling program (October 2009) groundwater samples (GW) were collected using a push point piezometer (AMS) inserted 4 m below the surface.

Samples were collected from the installed samplers using high density polyethylene (HDPE) 60 mL syringes attached to